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A Transformerless Adjustable Voltage Quadrupler Converter with Low Switch Voltage Stress

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ABSTRACT: A Transformerless adjustable voltage quadrupler converter which has high voltage gain and reduced stress across semiconductor components is presented in this report. Unlike conventional topologies, it has the advantage of automatic current sharing capability without addition of complex circuitry. The voltage stress across the active switches and diodes are reduced to a great extend which indeed enhance its conversion efficiency. It is capable of providing Voltage gain of four times as conventional boost converters hence named Quadrupler converter. Therefore one can choose low voltage rating switches and diodes to reduce both switching and conduction losses. This converter utilises interleaved structure hence allowing high frequency operation and operates in continuous conduction mode (CCM) with duty ratio greater than 0.5. MATLAB R2014a version software is used to simulate the model.

KEYWORDS: Quadrupler, automatic current sharing capability, interleaved structure, CCM

I. INTRODUCTION

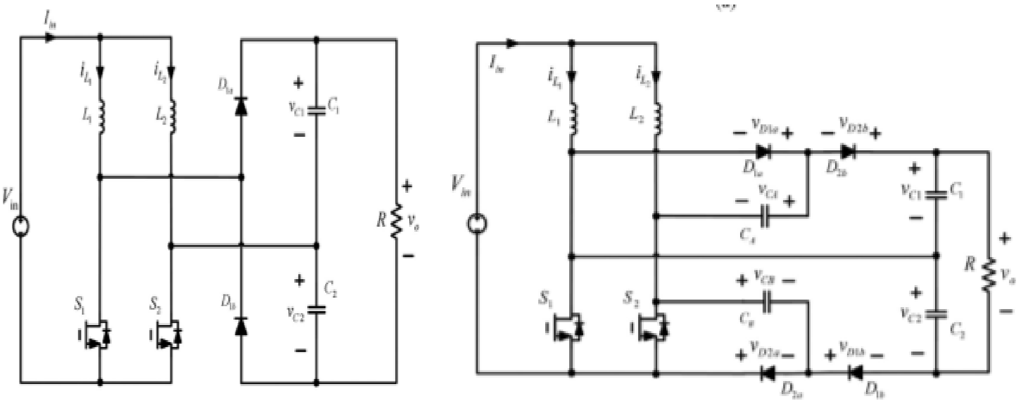
With the shortage of the energy and ever increasing oil price, research on the renewable and green energy sources, especially the solar arrays and the fuel cells, becomes more and more important. Photovoltaic (PV) sources are one of the significant players in the worlds energy contributors and will become the biggest to the electricity generation among all renewable energy candidates by year 2030 as it is truly a clean and emission-free renewable electrical generation technology with high reliability [3]. However, due to the inherent low voltage characteristic of these sources, a high step-up dc converter is essential. There are some limitations for the conventional boost converter in high step-up DC-DC conversion because of its extremely high duty ratio such as the current ripples of the switches and the output diodes are large, the switch voltage stress is equal to the output voltage, which is large in high output voltage applications and the switching losses and the output diode losses are large due to the hard switching operation and high switch voltage stress.[2]Therefore many topologies have been introduced to provide a high step-up voltage gain without an extremely high duty ratio. Initially a dc-dc fly-back converter with a very simple isolated structure and with a high step-up voltage gain was introduced, but the switches that are active, of this converter will suffer a high voltage stress due to the leakage inductance of the transformer. Next came some existing isolated voltage type converters, such as the phase-shifted full-bridge converters, can achieve a high step-up gain by incrementing the turns ratio of the transformer.[2] Unfortunately, the higher input current ripples existing reduces the maximum output power and shorten the usage life of input electrolytic capacitor. Furthermore, voltage stress across the output diode is much higher than the output voltage, which will degrade the circuit efficiency.

The switched capacitor-based converters provide solutions to improve the conversion efficiency and achieve large voltage conversion ratio. Unfortunately, the conventional switched capacitor technique makes the switch suffer high transient current and large conduction losses. Furthermore, many switched capacitor cells are required to obtain extremely high step-up conversion, which increases the circuit complexity. Then attention was focussed onto soft switching schemes and interleaved structures.[5][6].The interleaved voltage doubler for universal line power factor correction front end with automatic current sharing capability and lower active switch stress to increase the low-line efficiency. However, the voltage gain is not high enough and the diode voltage stress remains very high. Inorder to rectify all these problem a new converter called Quadrupler Converter was introduced. It integrates two-phase interleaved boost converter to realize a high voltage gain and maintain the advantage of an automatic current sharing capability simultaneously. Furthermore, the voltage stress of active switches and diodes in the converter can be greatly reduced to enhance overall conversion efficiency.

Using synchronous rectification technology the the diodes are replaced by mosfets so that the diode conduction losses are eliminated there by the efficiency of the converter is improved.

II. QUADRUPLER CONVERTER TOPOLOGY

The converter topology is developed from a two-phase interleaved boost converter and is shown in Figure 1(a)



(a) (b)

Figure 1. Configuration of (a) Two-phase interleaved boost converter (b) the Quadrupler Converter

Comparing Figure 1(a) with Figure 1(b) one can see that two more capacitors and two more diodes are added so that during the energy transfer period inductor stored energy partially is stored in one capacitor and partial inductor energy stored together with the other capacitor store energy is transferred to the output so as to achieve much higher voltage gain. However, the voltage gain is twice that of the interleaved two-phase boost converter. Also, the voltage stress of both active switches and diodes are much lower than the latter. Furthermore, as will be obvious latter, the quadrupler converter possesses automatic uniform current sharing capability without adding any extra circuitry or complex control methods. These characteristics can be achieved for the duty cycle greater than 0.5 and in continuous conduction mode (CCM); hence, the steady-state analysis is made only for this case. Basically, the operating principle of the converter can be classified into four operation modes. The interleaved gating signals with a 180° phase shift as well as some key operating waveforms are shown in Figure 3.

Mode 1 ($t_0 \leq t < t_1$)

For mode 1, switches S_1 and S_2 are turned ON, D_{1a}, D_{1b}, D_{2a}, D_{2b} are all OFF. The equivalent circuit that corresponds is shown in Figure 2(a). From Figure 3, it is seen that both i_{L1} and i_{L2} increases to store energy in L_1 and L_2, respectively. The voltages across diodes D_{1a} and D_{2a} are clamped to capacitor voltage V_{CA} and V_{CB}, respectively, and the voltages across the diodes D_{2a} and D_{2b} are clamped to V_{C2} minus V_{CB} and V_{C1} minus V_{CA} , respectively. Also, the load power is supplied from capacitors C_1 and C_2.

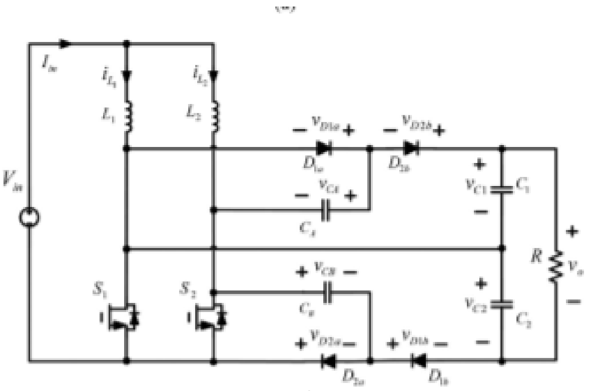


Figure 2 (a) Mode 1 and 3 of the Quadrupler Converter

Mode 2 ($t_1 \le t < t_2$)

For this operation mode, switch S_1 remains conducting and S_2 is turned OFF. Diodes D_{2a} and D_{2b} become conducting. The equivalent circuit corresponding to it is shown in Figure 2(b). It is seen from Figure 3 that part of stored energy in inductor L_2 as well as the stored energy of C_A is now released to output capacitor C_1 and load. Meanwhile, part of stored energy in inductor L_2 is stored in C_B. In this mode, capacitor voltage V_{C1} is equal to V_{CB} plus V_{CA}. Thus, i_{L1} still increases continuously and i_{L2} decreases linearly.

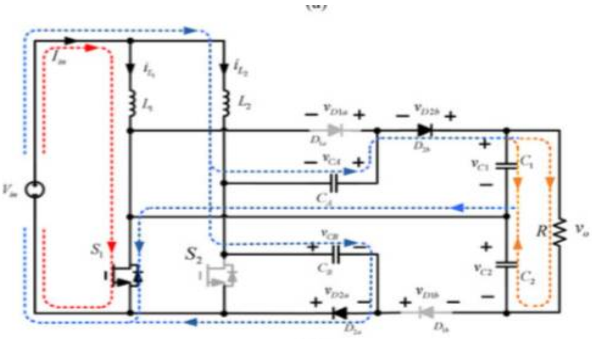


Figure 2 (b) Mode 2 of the Quadrupler Converter

Mode 3 ($t_2 \le t < t_3$)

For this operation mode, as can be observed from Figure 3, both S_1 and S_2 are turned ON. The corresponding equivalent circuit turns out to be the same as Figure 2(a).

Mode 4 ($t_3 \le t < t_4$)

For this operation mode, switch S_2 remains conducting and S_1 is turned OFF. Diodes D_{1a} and D_{1b} become conducting. The corresponding equivalent circuit is shown in Figure 2(c). It is seen from Figure 2(c) that the part of stored energy in inductor L_1 as well as the stored energy of C_B is now released to output capacitor C_2 and load. Meanwhile, part of stored energy in inductor L_1 is stored in C_A. In this mode, the output capacitor voltage V_{C2} is equal to V_{CB} plus V_{CA}. Thus, i_{L2} continue to increase and i_{L1} decreases linearly.

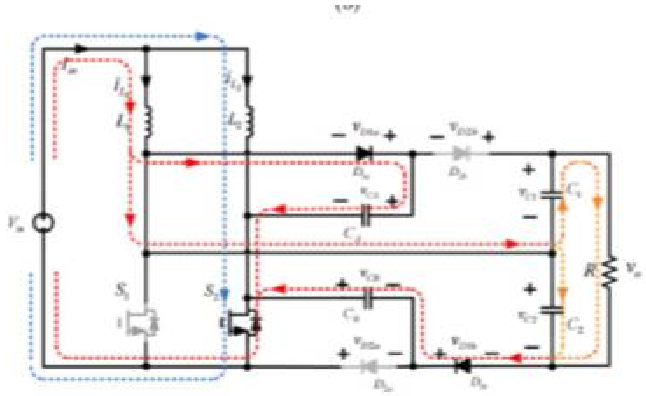


Figure 2(c) Mode 4 of the Quadrupler Converter

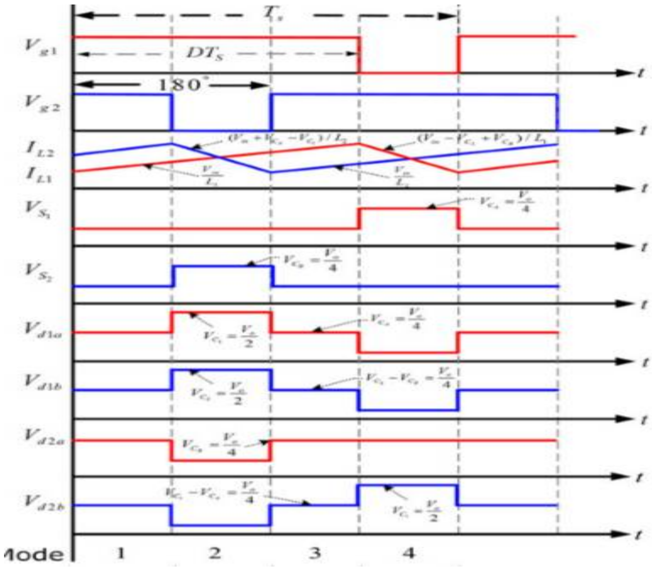


Figure 3 Equivalent waveform of the Quadrupler Converter

STEADY STATE ANALYSIS

Voltage Gain

Referring to Figure 2 (a) and 2 (c), from the volt-second relationship of inductor L_1 (or L_2), one can obtain the following relations:

$$V_{in}D + (Vin - V_{CA}) (1-D) = 0 \text{ .... } (1)$$
$$V_{in}D + (Vin - V_{CB}) (1 - D) = 0 \text{........ } (2)$$

Also from the equivalent circuits in Figure 2 (b) and 2 (c), voltage V_{C1} and V_{C2} can be derived as follows by substituting the V_{CA} and V_{CB} solutions of (1) and (2):

$$V_{C1} = V_{CA} + V_{CB} = \frac{2}{1-D} V_{in} \text{ .... } (3)$$

$$V_{C2} = V_{CA} + V_{CB} = \frac{2}{1-D}V_{in} \text{.........} \quad (4)$$

It follows from (3) and (4) that the output voltage can be obtained as follows :

$$Vo = V_{C1} + V_{C2} = \frac{4}{1-D}V_{in} \text{ ....} \quad (5)$$

Thus, the voltage conversion ratio M of the quadrupler converter can be obtained as follows:

$$M = \frac{V_o}{V_{in}} = \frac{4}{1-D} \text{ ....} \quad (6)$$

Voltage Stresses on Semiconductor Components

From Figure 2(a) and 2(b), one can see that the voltage stresses on active power switches S_1 and S_2 can be obtained directly as shown in the following equation:

$$V_{S1,\,max} = V_{S2,\,max} = \frac{1}{1-D}V_{in} \text{ ....} \quad (7)$$

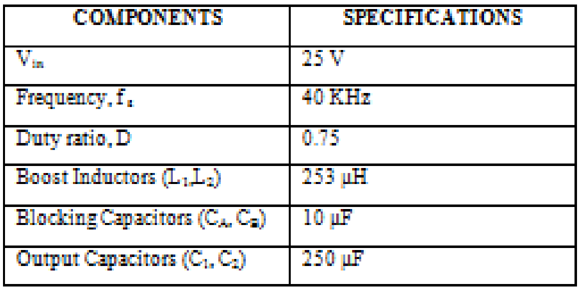
Substituting (4) into (7), the voltage stresses on the active power switches can be expressed as

$$V_{S1,\,max} = V_{S2,\,max} = \frac{V_o}{4} \text{ ....} \quad (8)$$

From (2.26), one can see that the voltage stress across switches of the converter is equivalent to one fourth of the output voltage. The open circuit voltage stress of diodes D_{1a}, D_{2a}, D_{1b}, and D_{2b} can be obtained directly as shown in (9).

$$V_{D1a,\,max} = V_{D1b,\,max} = V_{D2b,\,max} = \frac{V_o}{2};\ V_{D2a\,,max} = \frac{V_o}{4} \text{ ....} \quad (9)$$

Design Procedure



COMPONENTS	SPECIFICATIONS
V_{in}	25 V
Frequency, f_s	40 KHz
Duty ratio, D	0.75
Boost Inductors (L_1,L_2)	253 µH
Blocking Capacitors (C_A, C_B)	10 µF
Output Capacitors (C_1, C_2)	250 µF

III. SIMULATION RESULTS

The Quadrupler converter is simulated using MATLAB/ SIMULINK. The switching frequency is chosen to be 40 kHz, both duty ratios of S_1 and S_2 equal to 0.75 (should be greater than 0.5). The interleaved gating signals have a phase shift of 180 . The input voltage given is 25 V, and the output voltage obtained is to be 400 V. The Simulation Diagram and results are given below.

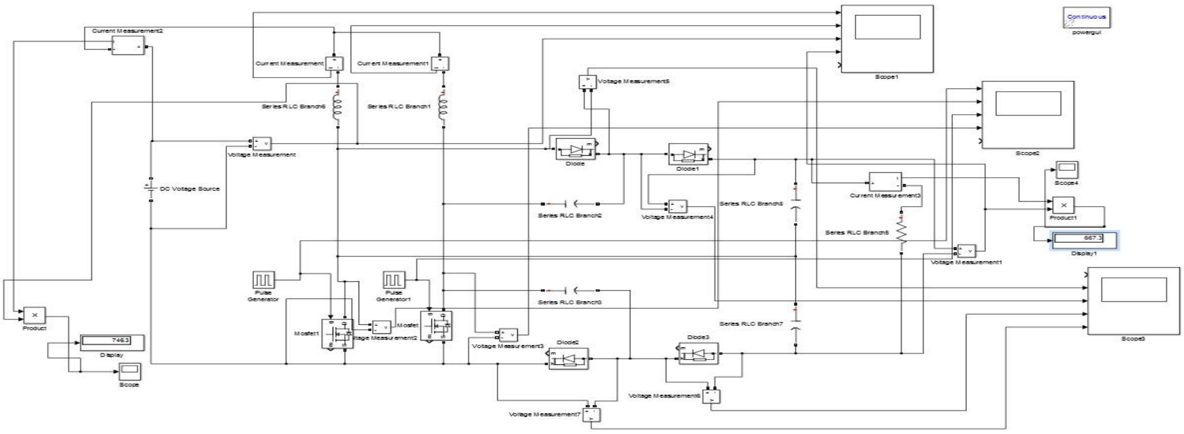


Figure 4. Simulink model of the Quadrupler Converter

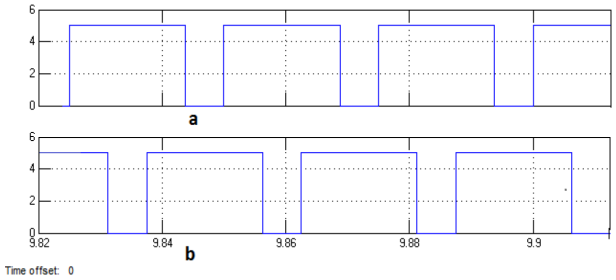


Figure 5. Gate pulse given to the Quadrupler Converter (a) for switch S_1 (b) for switch S_2

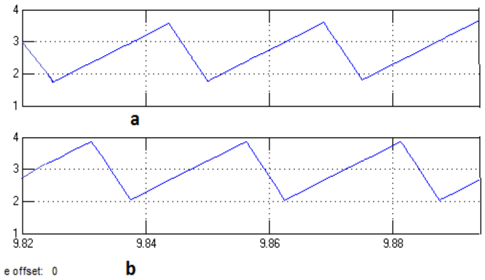


Figure 6: Inductor Currents (a) I_{L1} (b) I_{L2}

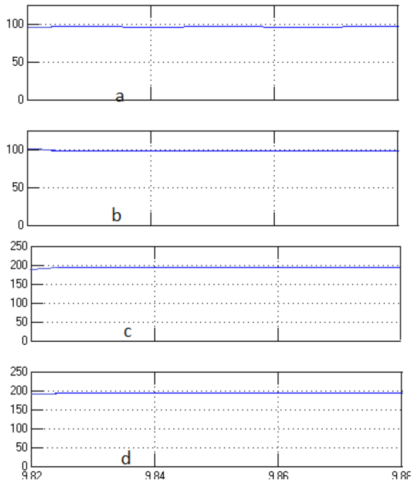


Figure 7: Waveform of Output Capacitors Voltage (a) V_{C1} (b) V_{C2} and Blocking Capacitors Voltages (c) V_{CA} (d) V_{CB}

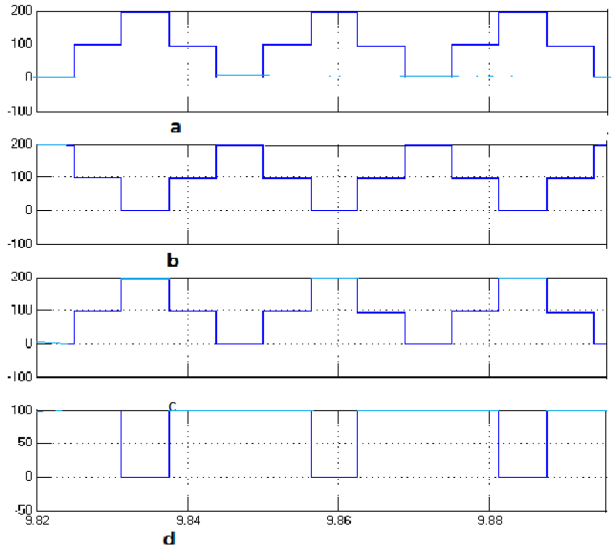


Figure 8 : Waveform of Voltage Stress of Diodes (a) V_{D1a} (b) V_{D1b} (c) V_{D2b} (d) V_{D2a}

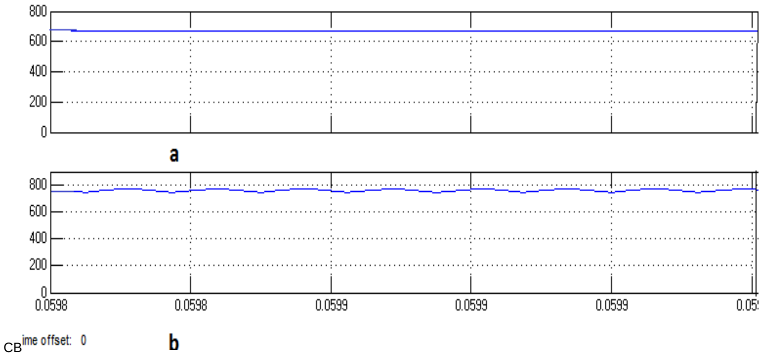


Figure 9 (a) Output Power and (b) Input Power

For an input voltage of 25 V an output voltage of 400 V is obtained. From the simulation results it was observed that the output power for input power of 763.1 W is obtained as 667.1 W. Therefore the conversion efficiency was found to be 87.4%

Modified Circuit

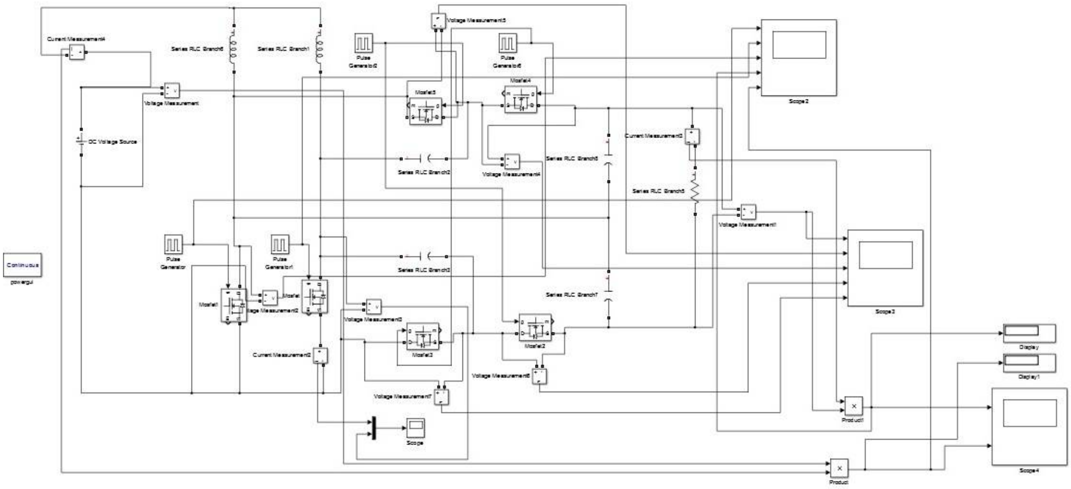


Figure 4. Simulation model of the improved Quadrupler Converter

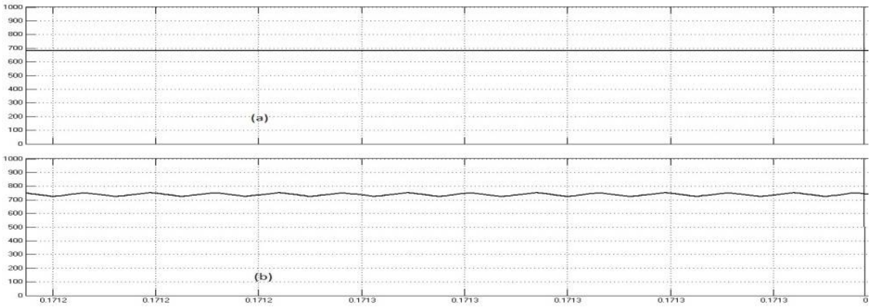


Figure 11 (a) Output Power and (b) Input Power

In order to increase the converter efficiency one can adopt the synchronous rectifier technology namely replace four diodes with four MOSFETS. For the same parameters the diodes were replaced by mosfets and the efficiency was found to be increased to 94.2 %.

IV. CONCLUSIONS

Quadrupler topology utilizes input-parallel output-series configuration and is derived from a two-phase interleaved boost converter for providing a much higher voltage gain without adopting an extreme large duty cycle. The converter cannot only achieve high step-up voltage gain but also reduce the voltage stress of both active switches and diodes. For input voltage of 25 V, output voltage of 400 V is obtained with an efficiency of 87.42 %. Maximum switching stress was found to be 100 V (i.e, one fourth of output voltage) and diode stress was found to be between 100 V and 200 V. The converter efficiency was improved by replacing diodes with mosfets and was found to be 94.2 %. Quadrupler converter can be used for High voltage, low Power applications-as converter interfacing fuel cell and PV cell output, battery backup systems for UPS, high intensity discharge lamp ballast for automobile head lamps

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